Developing a Systems-Science Methodology for the Statistical Data Analysis of the Solar-Wind-Driven Magnetosphere: *A Stock Market of Earth Measurements*

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1. The study of solar-wind driving of the magnetosphere
2. Introduce the stock market of Earth measurements
3. CCA: tool for analyzing the driving of the market patterns by the solar wind.
4. Example market and early indications of patterns.

The Magnetosphere-Ionosphere System Is Driven by the Solar Wind

What does it mean that the magnetosphere is driven?

- **Convection occurs (magnetosphere and ionosphere)**
- **Plasma enters the magnetosphere from the solar wind**
- **Magnetic flux accumulates in the magnetotail**
- **Pressure buffeting**

Consequences of the driving:

- **Plasma transport and heating**
- **Internal current systems**
- **Morphology changes**
- **Aurora**
- **Substorms**
- **Energization of the radiation belts**
- **Ionospheric outflows**
- **Waves**
- **Etc.**

Traditionally, the Strength of the Driving Is Measured by Geomagnetic Indices

Geomagnetic indices are made from ground-based magnetometers measuring the size and locations of currents in the magnetosphere-ionosphere system.

Each index measures something different:

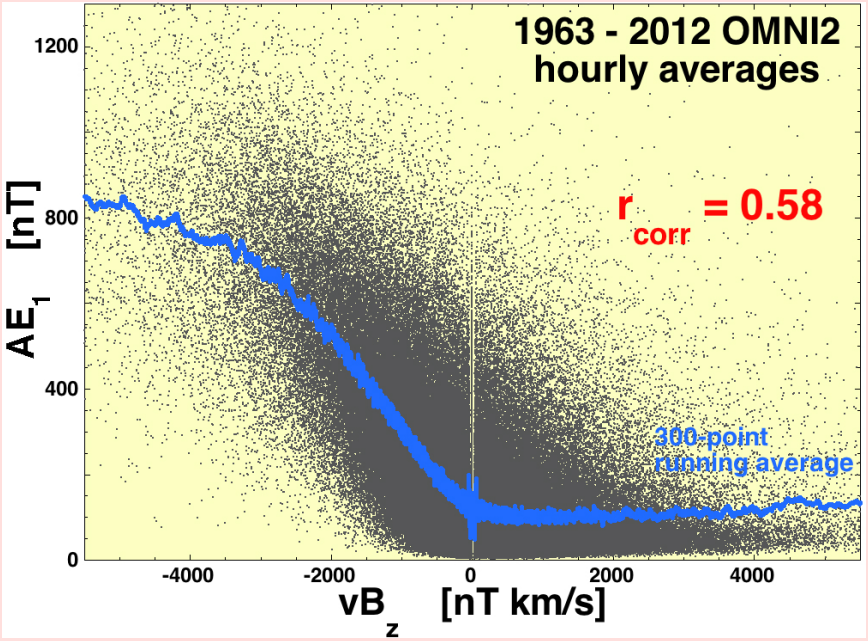
Kp index -- strength of magnetospheric convection
AL index -- nightside auroral activity
AU index -- high-latitude dayside current
Dst* index -- plasma pressure in the inner magnetosphere

Geomagnetic indices are used because they are simple and available.

Solar-Wind Coupling Functions

There is a search for the solar-wind formula that best describes the driving of the magnetosphere. These formulas are thought to describe the physics of the coupling.

These studies look at one solar-wind formula driving one geomagnetic index.



r_{corr} is the linear correlation coefficient: r_{corr}^2 is the amount of variance of one variable that is described by the variance of the other variable.

Note: vB_z describes only 33% of what is going on!

¿How can you develop any firm conclusions about the properties of the driven system with the majority of the behavior unaccounted for?

Motivation for the "Stock-Market" Approach to Studying Coupling

We see that multiple properties of the solar wind are involved in driving the Earth.

We see that the Earth responds in various manners.

Typically, one solar-wind formula and one index is studied: this is a very limited and inaccurate description.

In the spirit of "systems science", we want to look at the global reaction of the Earth to the solar wind.

Specifically, we will look at global correlations and correlation patterns between the magnetosphere and the solar wind.

The Financial Stock Market

What is a financial stock market?
A collection of measures of the values of companies.

A "stock-market index" can be created from the prices of the stocks in the market.

The market index can be used as an indicator of the state of the economy. It is a better indicator than the price of any one stock.

The market has trends, sectors (groups), patterns.

Sectors: high-tech stocks, financial stocks, mining stocks, energy stocks, industrials, healthcare, transportation, ...

People want to know how and why (a) individual stocks, (b) sectors, and (c) the stock market behave. They will look for causes in the "market driving forces".

An Earth Market

We want to create an "Earth market" that is a collection of measures of the magnetosphere-ionosphere system.

Let's call these individual measures "indices". Each index is a function of time.

A single "Earth-market index" or "whole-Earth index" can be created from the indices in the market. The market index is a function of time.

The market index can be used as an indicator of the state of the magnetosphere-ionosphere system. It may be a better indicator than a single index is.

The Earth market will have trends, sectors, patterns.

We want to know how and why (a) individual indices, (b) types of indices (sectors), and (c) the market index behave. We will look for causes in the solar wind.

Measures (Indices) We Have for the Earth Market

PCI -- polar cap current
AL -- nightside auroral-zone currents
AU -- dayside auroral-zone currents
MBI -- magnetospheric convection
Kp -- magnetospheric convection
Dst* -- plasma pressure
MPB – substorm currents
S_{geo} -- ULF geosynchronous
S_{gr} -- ULF ground
Wp -- Pi2 wave power
P_e -- hemispheric power of precipitating electrons
P_i -- hemispheric power of precipitating ions
Geosynchronous electron-radiation-belt number density
Geosynchronous electron-radiation-belt temperature
Geosynchronous electron-radiation-belt flux
TRBEC -- Total Radiation Belt Electron Content
Geosynchronous ion-plasma-sheet number density
Geosynchronous ion-plasma-sheet temperature
Substorm injected-electron number density at geosynchronous
Substorm injected-electron temperature at geosynchronous

Mathematical Basis of Our Analysis: Canonical Correlation Analysis (CCA)

CCA mathematically finds patterns of correlation between two multivariable data sets: Data Set 1 and Data Set 2.

Let Data Set 1 be the multivariable solar wind data set and let Data Set 2 be the multivariable Earth data set.

The solar wind data set has multiple variables that are intercorrelated with each other:

v, B_x, B_y, B_z, n, T_p, T_e, F10.7, S_p, M_A, α/p, δB, δv, ...

The Earth data set has multiple variables that are intercorrelated with each other:

AU, AL, PCI, Kp, MBI, Dst, ULF, ...

Canonical Correlation Analysis (CCA)

CCA creates a set of new solar-wind variables S_1, S_2, S_3, ... that are each linear combinations of the original solar-wind variables and CCA creates a set of new Earth variables E_1, E_2, E_3, ... that are each linear combinations of the original Earth variables.

The pair S_1 and E_1 are the "first canonical variables" of the combined system.

The pair S_k and E_k are the "kth canonical variables" of the combined system.

S_k and E_k are correlated with each other.

S_k has zero correlation with all other S_i and E_i unless i=k.

E_k has zero correlation with all other S_i and E_i unless i=k.

CCA and the Earth Market

The $E_1 \leftrightarrow S_1$ pair will be the strongest correlation between the solar wind and the Earth. E_1 will be the "Earth-market index" and S_1 will be the solar-wind coupling function that drives that index.

E_2 will be an internal trend in the Earth market and S_2 will be the solar-wind driver function for that internal trend.

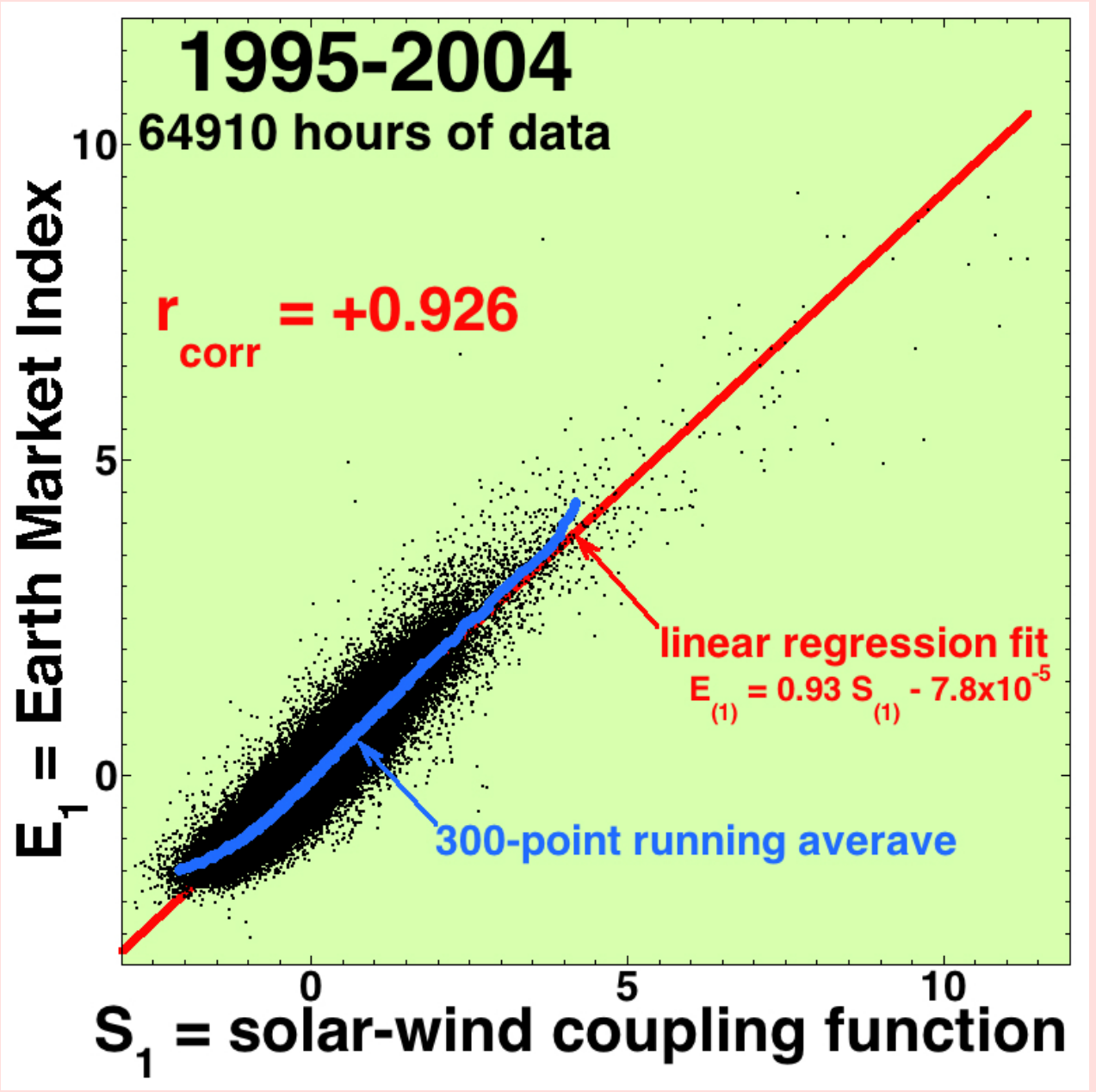
E_3 will be another internal trend in the market with solar-wind driver S_3.

E_4 will be another internal trend with driver S_4 .....

Example Earth Market

E_1 is a linear combination of:
$\log(AE_1)$
AU_1
AL_1
PCI_0
Kp_1
MBI_1
Dst_2*
S_{gr}
S_{geo}

S_1 is a linear combination of:
$\log(nv^2)$
$\log(n)$
$\langle \sin^2(\theta_{clock}/2) \rangle_3$
B_z
B_{mag}
$\langle \theta_{Bn} \rangle_3$
$\log(M_A)$
$\log(F10.7)$
$\int^{22hr} R_{quick}\, dt$



Trends Seen in Preliminary Work

First-order behavior: All individual geomagnetic indices increase in magnitude as the solar-wind coupling function S_1 increases.

Internal Pattern 1: High-latitude indices (AL, AU, PCI) and convection indices (MBI, Kp) act oppositely. Cause is that the clock angle of solar wind drives high-latitude indices more strongly and magnitude of solar-wind driver drives convection indices more strongly.

Internal Pattern 2: S_{gr} follows the behavior of the high-latitude indices and S_{geo} follows the behavior of the convection indices.

Internal Pattern 3: The flux of the electron radiation belt correlates with the difference S_{gr}-S_{geo} more than it correlates with S_{gr} or with S_{geo}.

Causality in Correlations

The measurements of the solar wind are imperfect and the various solar-wind quantities are intercorrelated.

A physically irrelevant variable may be carrying direct information about a relevant variable (confounding).

An physically irrelevant variable may be carrying information about noise in a relevant variable (suppression).

CCA has a methodology to get information about "causal correlations" versus "coincidental correlations" in such a data environment.

Program of Research

1. **Collect more measures of the magnetosphere-ionosphere system for a larger stock market.**

2. **Develop CCA methods based on Spearman-rank-order correlations and on mutual average information.**

3. **Introduce multiple internal time lags on solar-wind variables and on individual geomagnetic indices.**

4. **Develop better solar-wind driver functions.**

4. **Study the physics underlying the internal modes of the magnetosphere-ionosphere system.**

Acknowledgements

Giuseppe Consolini

Joachim Birn

Bob McPherron

Nikolai Østgaard

Jung-Chao Wang

Support

NASA Heliophysics LWS VarSITY

NSF GEM

Summary

1. An "Earth market" of multiple measures of the magnetosphere-ionosphere system is being created.

2. With CCA, internal trends in the Earth market can be identified and analyzed, and their causes in the solar wind can be identified.

3. New views of the reaction of the magnetosphere-ionosphere system to the solar wind are being uncovered.

4. With the addition of more indices into the Earth market, a more-global view of the behavior of the magnetosphere-ionosphere system will be seen.

Measures (Indices) We Can Get

Polar-cap size

Magnetospheric ion composition

Relativistic-electron precipitation

Magnetotail stretching

Substorm occurrence rate

ULF dawn-dusk

ULF compressive

Total hemispheric current

Ionospheric Joule heating

Global ionosonde indices

NOX

Physically, How Does the Solar Wind Couple to the Magnetosphere?

1. Via magnetic-field-line reconnection

    Magnetically connects the moving solar-wind plasma to the Earth.

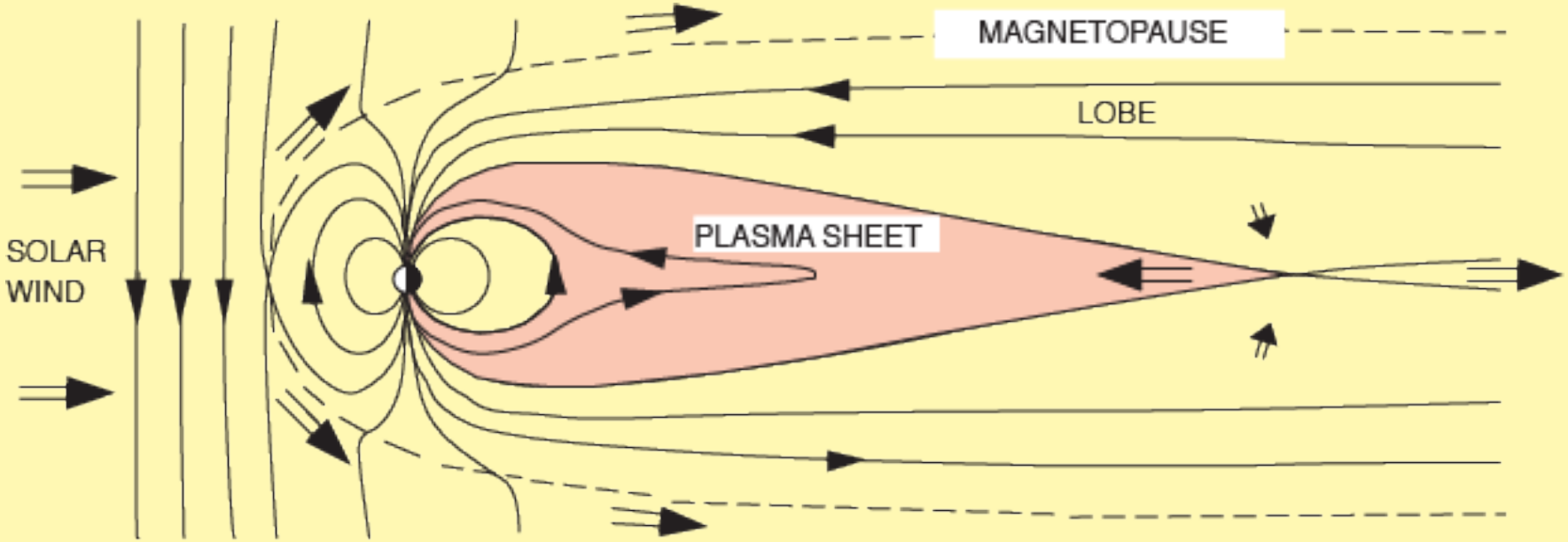
        1. Allows currents to flow from the solar wind into the magnetosphere.
        2. Allows solar-wind plasma to enter into the magnetosphere.

2. Via a viscous interaction

    A. particles diffuse across the magnetopause carrying momentum.

    B. Kelvin-Helmholtz ripples mix the plasma and magnetic field and tranport momentum.

A Sketch of the Solar-Wind Magnetic Field Reconnecting with the Magnetosphere



In steady state (or on average) there is a convection of flux through the magnetosphere.

Plasma convects with the magnetic flux.

There is an accompanying convection of the magnetic-field footpoints in the ionosphere.

Some Solar-Wind Variables that Drive the Earth

v_{sw} : geomagnetic activity is higher when the solar-wind speed is higher

B_{mag} : geomagnetic activity is higher when the magnetic-field strength is higher

θ_{clock} : geomagnetic activity is higher when the field direction is more southward.

n_{sw} : geomagnetic activity is higher when the solar-wind density is larger.

M_A : geomagnetic activity is lower when the Mach number is higher.

α/p : geomagnetic activity is higher when the alpha-to-proton ratio is higher.

δB : geomagnetic activity is higher when the amplitude of fluctuations in the solar wind is greater.

Some of these are physical, and some are coincidental. Determining causality from correlations is very difficult.